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From Einstein Nonlocality to von Neumann Reality *

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Abstract

Recent nonlocality results support a new picture of reality built on the ideas of John von Neumann.

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"Nonlocality gets more real". This is the provocative title of a recent report in Physics Today [1]. Three experiments are cited. All three confirm to high accuracy the predictions of quantum theory in experiments that suggest the occurrence of an instantaneous action over a large distance. The most spectacular of the three experiments begins with the production of pairs of photons in a lab in downtown Geneva. For some of these pairs, one member is sent by optical fiber to the village of Bellevue, while the other is sent to the town of Bernex. The two towns lie more than 10 kilometers apart. Experiments on the arriving photons are performed in both villages at essentially the same time. What is found is this: The observed connections between the outcomes of these experiments defy explanation in terms of ordinary ideas about the nature of the physical world *on the scale of directly observable objects.* This conclusion is announced in opening sentence of the Physical-Review-Letters report [2] that describes the experiment: "Quantum theory is nonlocal".

This observed effect is not just an academic matter. A possible application of interest to the Swiss is this: The effect can be used in principle to transfer banking records over large distances in a secure way [3]. But of far greater importance to physicists is its relevance to two fundamental questions: What is the nature of physical reality? What is the form of basic physical theory?

The answers to these questions depend crucially on the nature of physical causation. Isaac Newton erected his theory gravity on the idea of instant action at a distance. The idea was later banished from classical physics by Einstein's theory of relativity. However, the idea resurfaced at the quantum level in the debate between Einstein and Bohr. Einstein objected to the "mysterious action at a distance", but Bohr defended "the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality"[4].

The essence of this radical revision was explained by Dirac at the 1927 Solvay conference [5]. He insisted on the restriction of the application of

quantum theory to our knowledge of a system, not to that system itself. This view is encapsulated in Heisenberg's famous statement [6]:

"The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behaviour of the particle but rather our knowledge of this behaviour."

This conception of quantum theory, espoused by Bohr, Dirac, and Heisenberg, is called the Copenhagen interpretation. It is essentially subjective and epistemological, because the basic reality of the theory is 'our knowledge'.

It may seem odd at first that such prominent physicists would propose this radical revision of the nature of physical theory. But they seemed to be forced to this subjective point of view by certain failures of normal ideas about causation.

In actual practice, quantum theory often entails that an act of acquiring knowledge in one place instantly changes the theoretical representation of some faraway system. Physicists were—and are—reluctant to believe that performing a nearby act can instantly change a faraway physical reality. However, they know that "our knowledge" of a faraway system can instantly change when we acquire knowledge about a nearby system, provided some properties of two systems are known to be strongly correlated. For example, if we know that two particles start at the same time from the origin of the coordinate system, and subsequently travel with opposite velocities, then finding one of these particles at the point (x, y, z) allows us to 'know' that the other particle lies, at that same instant, at the point $(-x, -y, -z)$. But we do not imagine that the act of measuring the position of one particle *causes* the other particle to *be* where it is. By analogy, the instantaneous effects that automatically arise in quantum theory become less puzzling if one restricts the applications of quantum theory to "our knowledge", and renounces all efforts to understand physical reality, except to the extent that "physical reality" is identified with knowledge.

This way of dodging the locality problem was attacked by Einstein, Podol-

sky, and Rosen in a famous paper [7] entitled: “Can quantum-mechanical description of physical reality be considered complete?” Einstein and his colleagues argue that the answer to this question is No, while Bohr argues for the affirmative. Given the enormity of what must exist in the universe that is not “our knowledge”, it is astonishing that, in the minds of most physicists, Bohr has prevailed over Einstein in his claim that quantum theory, in a form that is explicitly restricted in application to human knowledge, can be considered to be a complete description of physical reality. This majority opinion stems, I believe, more from the lack of a promising alternative candidate than from any decisive logical argument.

Einstein, commenting on the Copenhagen position, said: “What I dislike about this kind of argument is the basic positivistic attitude, which from my view is untenable, and seems to me to come to the same thing as Berkeley’s principle, *esse est percipi* [9]. Many other scientists agree. For example, Murray Gell-Mann [10] asserts: “Niels Bohr brainwashed a whole generation into believing that the problem was solved fifty years ago”. Gell-mann has been pursuing with James Hartle [11] an ambitious program, built on ideas of Everett [12] and of Griffith [13], that aims to construct a quantum theory that is more complete than the Copenhagen version. This effort, and others like it, are fueled by the opinion that to integrate quantum theory into cosmology, and to understand the evolutionary process that has produced creatures that can have knowledge akin to “our knowledge”, one needs to have a theory of the evolving reality in which those creatures are imbedded.

It is in this context of such efforts to construct a more complete theory that the significance of the quantum nonlocality experiments lies. The point is this: If nature really is nonlocal, as these experiments suggest, then there is a simple theory of reality that encompasses both our knowledge and a real objective physical world in which that knowledge is embedded. It describes also the dynamical connection between these two aspects of reality. This theory is obtained by combining relativistic quantum field theory with the version of quantum theory developed by John von Neumann [14].

All physical theories are, of course, provisional, and subject to future revision or elaboration. But at a given stage in the development of science the contending theories can be evaluated on many grounds, such as utility, parsimony, predictive power, explanatory power, conceptual simplicity, logical coherence, and aesthetic beauty. The relativistic version of von Neumann's theory fares well on all of these counts.

The essential difference between von Neumann quantum theory and Copenhagen quantum theory lies in the way measuring devices are treated. In the Copenhagen approach, the measuring devices are excluded from the world described in the mathematical language of quantum theory. The measuring device are described, instead, by "the same means of communication as the one used in classical physics" [15]. This approach renders the theory pragmatically useful but physically obscure. It links the theory to "our knowledge" of the measuring devices in a useful way, but upsets the unity of the physical world. This tearing asunder of the physical world creates huge theoretical problems, which are ducked in the Copenhagen approach by renouncing man's ability to understand reality.

The mathematical rules of quantum theory specify clearly how the measuring devices are to be included in the quantum mechanically described physical world. Von Neumann first formulates rigorously the mathematical structure that quantum phenomena seem to force upon us, and then follows where that mathematics leads. It leads first to the incorporation of the measuring devices into the quantum mechanically described physical universe, and eventually to the inclusion of *everything* built out of atoms and their constiuents. Our bodies and brains thus become, in von Neumann's approach, parts of the quantum mechanically described physical universe. Treating the entire physical universe in this unified way provides a conceptually simple and logically coherent theoretical foundation. The Copenhagen alternative of leaving out of this description parts of the physical universe that are interacting with the parts retained severely disrupts the logical coherence of the theoretical structure.

Copenhagen quantum theory claims to be complete. That claim stems from the fact that all of validated predictions of classical physical theory can deduced from it, together with a host of quantum predictions, many validated, and none known to fail. Bohr argues that all possible predictions pertaining to connections between outcomes of human observations of the devices that probe atomic systems are obtainable from Copenhagen quantum theory.

Von Neumann quantum theory encompasses, in principle, all of the prediction of Copenhagen quantum theory. It postulates, for each observer, that each increment in his knowledge is connected to a corresponding 'reduction' of the state of his brain: the new reduced state is obtained from the old state by eliminating all parts that are incompatible with his new knowledge. This rule is a direct application, at the level of the brain of the observer, of the rule that Copenhagen quantum theory applies at the level of the measuring device, and the equivalence is the two formulations arises from the causal connection that is needed to effect a good observation.

But von Neumann quantum theory gives, in principle, much more than Copenhagen quantum theory can. By providing an objective description of the entire history of the universe, rather than merely rules connecting human observations, von Neumann's theory provides a quantum framework for cosmological and biological evolution. And by including the body and brain of the observer as well as his knowledge, and also the dynamical laws that connects these two realities, the theory provides a coherent framework for understanding the relationship between mind and matter [16].

Von Neumann's rules are, of course, expressed in neat mathematical form. [See Box 1]

Box 1: von Neumann Quantum Theory

The evolving state of the universe is represented by an operator S(t).

The state of any subsystem, b, is represented by

$$S_b(t) = Tr_b S(t),$$

where Tr_b stands for the partial trace over all variables other than those that define the subsystem b.

The system S(t) evolves between reductions via the equation

$$S(t + \Delta t) = \exp(-iH\Delta t)S(t)\exp(+iH\Delta t),$$

where H is the energy operator. Each reduction is associated with a quantum information processor b and a projection operator P that acts like the identity on all degrees of freedom other than those that define b. The reduction proceeds in two steps. First a question is posed by the processor. This is represented by the von Neumann process I: if $S(t - 0)$ is the limit of $S(t')$ as t' approaches t from below then

$$S(t) = PS(t - 0)P + (1 - P)S(t - 0)(1 - P).$$

Then nature chooses an answer, $P = 1$ or $P = 0$, according to the rule

$S(t + 0) = PS(t)P$ with probability $TrPS(t)/TrS(t)$,

or

$S(t + 0) = (1 - P)S(t)(1 - P)$ otherwise.

Reconciliation with Relativity

von Neumann quantum theory gives a logically simple mathematical description of an evolving physical world that is linked to human experiences by specified dynamical equations. But there is one major problem: reconciliation with the theory of relativity. This problem arises from the fact that von Neumann formulated his theory in the nonrelativistic approximation.

The problem has two parts. The first is resolved by simply replacing the nonrelativistic theory used by von Neumann with relativistic quantum field theory. To deal with the link to human knowledge, and hence to the predictions of Copenhagen quantum theory, one needs to consider human brains.

Quantum electrodymamics is the relevant field theory, and the pertinent energy range is that of atomic and molecular interactions. I shall assume that whatever high-energy theory eventually prevails in quantum physics, it will reduce to quantum electrodynamics in this regime.

The second problem is this: von Neumann's theory is built on the Newtonian concept of the instants of time, 'now', each of which extends over all space. The evolving state of the universe S(t) is defined to be the state of the entire universe at the instant of time t. The formulations of relativistic quantum field theories by Tomonaga [17] and Schwinger [18] have corresponding spacelike surfaces σ. As Pauli once strongly emphasized to me, these surfaces, while they may give a certain aura of relativistic invariance, do not differ significantly from the constant-time surfaces that appear in the nonrelativistic approximation. Indeed, all efforts to eliminate from quantum theory this preferred status of time have proved futile.

To obtain a relativistic version of von Neumann's theory one needs to identify von Neumann's constant-time surfaces with certain special spacelike surfaces σ of the formulations of Tomonaga and Schwinger. To achieve an *objective* quantum theory of reality theory, these preferred instants *now* must be objective features of nature.

Giving special physical status to a particular sequence of spacekike surfaces runs counter to certain ideas spawned by the theory of relativity. However, the astronomical data [19] indicates that there is a preferred sequence of 'nows' that define spacelike surfaces in which, for the early universe, matter was distributed almost uniformly in density, mean local velocity, and temperature.

I shall assume that there is a preferred advancing sequence of spatial surfaces, and that in the early universe these surfaces are defined by the cosmologically preferred frame.

Nonlocality and Relativity

This theory immediately accounts for the faster-than-light transfer of information that seems to be entailed by the nonlocality experiments: the

reduction of the state S(t) of the universe on the occasion of the earlier of the two measurement, which (in the cited experiment) occurs in one of the two villages, has, according to this theory, an immediate effect on the evolving state S(t) of the universe, and hence an immediate effect also on the propensities for the various possible outcomes of the measurement performed slightly later in the other village.

Such an instantaneous transfer of information is widely held to be impossible: it is believed to violate the precepts of the theory of relativity. But does it?

The theory of relativity was originally formulated within classical physical theory, and, in particular, for a deterministic theory. In that case the entire history of the universe could be conceived to be laid out for all times in a four-dimensional spacetime. The idea of "becoming", or of the gradual unfolding of reality, has no natural place in this deterministic conception of the universe.

Quantum theory is a different kind of theory: it is formulated as an indeterministic theory. Determinism is relaxed in two ways. First of all, freedom is granted to experimenters to chose which measurements they will perform. Second, Nature is then required to choose the outcome of any experiment that is actually performed, subject to statistical conditions. Nature is not required to choose an outcome for a contemplated alternative possible experiment that is not actually performed.

In view of these deep structural differences there is a question of principle regarding how the idea of no faster-than-light transfer of information should be carried over from the deterministic classical idealization to the indeterministic quantum reality.

Relativistic quantum field theory is the canonical relativistic generalization of nonrelativistic quantum theory. That theory has two key relativistic properties: (1), All of its predictions about outcomes of measurements are independent of the coordinate frame used to define the advancing sequence of constant-time surfaces 'now'; and (2), No *signal* can be transmitted faster

than light. [A "signal" is a *controllable* transfer of information: it is a transfer that allows a sequence of bits composed by a sender to be conveyed to a receiver.] However, the theory explicity exhibits other transfers of information that do not conform to the no-faster-than-light rule. These transfers are associated with the reduction events. Within the theory these transfers act instantaneously along the spatial slices of Tomonaga and Schwinger, once this sequence of advancing constant-time surfaces σ is fixed. The locus of these transfers can be shifted by shifting these surfaces, but, within the theory, these transfers cannot be eliminated.

As mentioned above, the usual way of dealing with these explicit faster-than-light-transfers in relativistic quantum field theory is to say that their appearance shows that the theory cannot be interpreted realistically: the theory *must* be about "our knowledge", as Bohr and company claim, rather that about reality itself. There is no puzzle about the fact that our knowledge about a faraway system can suddenly change when we acquire here information about some system that is strongly correlated with that far away system. But it is maintained that reality itself cannot behave in this way.

That is indeed the widely held prejudice. But there is no theoretical or empirical evidence that supports it. Indeed, both theory and the nonlocality experiments appear to contradict it. It is thus a metaphysical prejudice with no scientific basis. Scientific theories should be judged on the basis of the criteria mentioned above, rather than on the basis of a pure metaphysical prejudice. Renouncing our ability to understand the world around us is a price too heavy to pay to preserve a mere prejudice.

If that metaphysical prejudice is wrong, then all of the contortions and evasions and renunciations that characterize the subjective Copenhagen interpretation can be discarded: one can reaffirm, with Einstein, the traditional idea that we should pursue, without self-imposed limitations, our efforts to understand the world around us and our connection to it: if that metaphysical prejudice is wrong then we can return to the idea that the proper goal of science is to understand the objectively existing reality of which 'our

knowledge' is a tiny part.

Is Nonlocality Real?

The claim that von Neumann's theory can describe objective reality rests heavily on the assumption that nonlocality is real. But how strong is the evidence for this? Is there really any credible evidence that information is transferred over spacelike intervals?

The evidence is very strong that the predictions of quantum theory are valid in these experiments involving pairs of measurementss performed at essentially the same time in regions lying far apart. But the question is this: Can we validly argue from the empirically supported premise that these predictions of quantum theory are correct to the conclusion that nature must transfer information over spacelike intervals?

The usual arguments for nonlocality stem from the work of John Bell [20]. Pondering the issue debated by Einstein and Bohr, Bell proposed the following approach: Assume that quantum theory is indeed incomplete, as Einstein claimed, and hence that there are variables other than those that appear in Copenhagen quantum theory. Then formulate a locality requirement in terms of these extra variables, which are then called "local hidden variables", and prove that the existence of such variables is incompatible with the assumed validity of certain predictions of quantum theory.

Bell was able to prove such a contradiction. This proof showed, basically, that Einstein was wrong: Einstein's asssumption that quantum theory is both incomplete and local is not viable.

But that sort of argument is no proof, or even indication, that quantum theory is nonlocal. The more plausible conclusion, for quantum physicists, is that nature is local, but that Einstein was wrong in claiming that quantum theory is incomplete: the hidden-variable assumption is wrong.

Eliminating Hidden Variables

The argument of Bell is essentially different from that of Einstein, Podolsky, and Rosen. The former shows the ideas of Einstein cannot all be correct; the latter aimed to show that the ideas of Bohr cannot all be correct.

The problem faced by Einstein and his colleagues was to mount *within the quantum framework* an argument that involved a consideration of possible outcomes of *alternative* possible experiments. The difficulty is that quantum philosophy explicity rejects the notion that the outcomes of two alternative possible measurements are both physically well defined. Indeed, that limitation was precisely the idea that Einstein and company wanted to challenge. But then they had to mount an argument that dealt with alternative possible measurements without contravening *in their premises* the very precept that they were challenging.

Their strategy was to introduce the outcomes of alternative possible experiments via a locality requirement on physical reality that seemed undeniable. The strategy succeeded: Bohr was forced into a very fragile position that depended upon entangling physical reality with predictions, and hence with knowledge:

"*...an influence on the very conditions which define the possible types of predictions regarding future behavior of the system.* Since these conditions constitute an inherent element of any phenomena to which the term 'physically reality' can be properly attached we see that the argument of mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete."[8]

I shall pursue here a strategy similar to that of Einstein and his colleagues, and will be led to a conclusion similar to Bohr's, namely that quantum physical reality is entwined with knowledge, and does involve some subtle sort of nonlocal influence.

I introduce alternative possibilities by combining two ideas embraced by Copenhagen philosophy. The first of these is the freedom of experimenters to choose which measurements they will perform. In Bohr's words:

"The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangements for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude."[15]

This assumption lies at the foundation for Bohr's notion of complementarity: some information about all the possible choices is simultaneously present in the quantum state, and Bohr wants to provide the possibility that any one of the mutually exclusive alternatives might be used. No matter which choice the experimenter makes, the associated set of predictions is supposed to hold.

The second idea is the condition of no backward-in-time causation. According to quantum thinking, experimenters are to be considered free to choose which measurement they will perform. Moreover, if an outcome of a measurement appears to an observer at a time earlier than some time T, then this outcome can be considered to have been fixed independently of which experiment will be *freely chosen* and performed by another experimenter at times later than T: the later choice is allowed go either way without disturbing the outcome that has already appeared to observers earlier. For whichever choice is eventually made at the later time, the relevant prediction of quantum theory is supposed hold. This no-backward-in-time influence condition is assumed to hold for at least one coordinate system (x,y,z,t).

These two conditions are, I believe, compatible with quantum thinking. They contradict no quantum precept or combination of quantum predictions. They, by themselves, lead to no contradiction. But they do involve the contemplation of alternative possibilities, and provide the needed logical toehold.

The Hardy Experimental Setup

To get a nonlocality conclusion like the one obtained from Bell-type theorems, but without contravening the precepts of quantum theory, it is easiest to consider an experiment of the kind first discussed by Lucien Hardy [21]. The setup is basically similar to the ones considered in proofs of Bell's theorem. There are two spacetime regions, L and R, that are "spacelike separated". This condition means that the two regions are situated far apart in space relative to their extensions in time, so that no point in either region can be reached from any point in the other without moving either faster than the speed of light or backward in time. This means also that in some

frame, which I take to be the coordinate system (x,y,z,t) mentioned above, the region L lies at times greater than time T, and region R lies earlier than time T.

In each region an experimenter freely chooses between two possible experiments. Each experiment will, if chosen, be performed within that region, and its outcomes will appear to observers within that region. Thus neither choice can affect anything in the other region without there being some influence that acts over a space-like interval.

The argument involves four predictions made by quantum theory under the Hardy conditions. These conditions are described in Box 2.

Box 2: Predictions of quantum theory for the Hardy experiment.

The two possible experiments in region L are labelled L1 and L2.

The two possible experiments in region R are labelled R1 and R2.

The two possible outcomes of L1 are labelled L1+ and L1-, etc.

The Hardy setup involves a laser down-conversion source that emits a pair of correlated photons. The experimental conditions are such that quantum theory makes four (pertinent) predictions:

1. If (L1,R2) is performed and L1- appears in L then R2+ must appear in R.
2. If (L2,R2) is performed and R2+ appears in R then L2+ must appear in L.
3. If (L2,R1) is performed and L2+ appears in L then R1- must appear in R.
4. If (L1,R1) is performed and L1- appears in L then R1+ appears sometimes in R.

The three words "must" mean that the specified outcome is predicted to occur with certainty (i.e., probability unity).

Two Simple Conclusions

It is easy to deduce from our assumptions two simple conclusions.

Recall that region R lies earlier than time T, and that region L lies later than time T.

Suppose the actually selected pair of experiments is (R2, L1), and that the outcome L1- appears in region L. Then prediction 1 of quantum theory entails that R2+ must have already appeared in R prior to time T. The no-backward-in-time-influence condition then entails that this outcome R2+ was fixed and settled prior to time T, independently of which way the later free choice in L will eventually go: the outcome in region R at the earlier time would still be R2+ even if the later free choice had gone the other way, and L2 had been chosen *instead of* L1.

Under this alternative condition (L2,R2,R2+) the experiment L1 is not performed, and there is no physical reality corresponding to its outcome. But in this alternative case L2 is performed, and hence L2 must have an outcome. Prediction 2 of quantum theory asserts that it must be L2+. This yields the following conclusion:

Assertion A(R2):

If (R2,L1) is performed and outcome L1- appears in region L, then if the choice in L had gone the other way, and L2, instead of L1, had been performed in L then outcome L2+ would have appeared there.

Because we have two predictions that hold with certainty, and the two strong assumptions of 'free choice' and 'no backward causation', it is not surprising that we have been able to derive this conclusion. In an essentially deterministic context we are often able to deduce from the outcome of one measurement what would have happened if we had made, instead, another measurement. If the actual outcome has a unique *precondition*, which leads to a unique outcome of the alternative possible measurement then we can draw a conclusion of this kind.

Consider next the same assertion, but with R2 replaced by R1:

Assertion A(R1):

If (R1,L1) is performed and outcome L1- appears in region L, then if the choice in L had gone the other way, and L2, instead of L1, had been performed in L then outcome L2+ would have appeared there.

This assertion cannot be true. The fourth prediction of quantum theory asserts that under the specified conditions, L1- and R1, the outcome R1+ appears sometimes in R. The no backward-in-time-influence condition ensures that this earlier fact would not be altered if the later choice in region L had been L2. But A(R1) asserts that under this altered condition L2+ would appear in L. The third prediction then entails that R1- must always appear in R. But that contradicts the earlier assertion that R1+ sometimes appears in R.

The fact that A(R2) is true and A(R1) is false means that the choice made in region R between R2 and R1 converts from necessarily true to necessarily false a statement whose truth or falsity is determined wholly by connections between possible events located in a region L that is spacelike separated from the region R where the choice between R2 and R1 is made. This is a theoretical constraint on any model that satisfies the assumptions of the proof. It means that any model that satisfies these assumptions must have some way of transferring information from region R to region L.

Stated more physically, our assumptions entail the existence of a constraint connecting the outcomes that nature can choose in region L under the different conditions that the experimenter in region L can choose to set up there, and this constraint takes one or the other of two incompatible forms depending on whether the experimenter in region R chooses to perform experiment R1 or R2.

It can be concluded that any model of nature that conforms to the predictions and general precepts of quantum theory embodied in our assumptions must accomodate tranfers of information over spacelike intervals. Hence the presence of such transfers in a putative objective theory of reality not only does not disqualify the theory, but constitutes, rather, a necessary property:

any theory of reality that satisfies the assumptions of the proof must provide for tranfers of information of the kind demanded by the proof.

The physical basis of the argument is the set four predictions of quantum theory. Although the *derivation* of these predictions involves quantum entities, such as photons, it is only the predictions themselves, not their derivation, that enter into the argument. These predictions are about large-scale experiments and large scale outcomes. Thus the argument itself is expressed completely in terms of big things. It shows that certain classical ideas about causation cannot be maintained for big objects separated by large distances.

The World as Knowledge

The objective quantum theory discussed here rejects the Copenhagen renunciation of our ability to understand the objective sources of our knowledge. But it accepts many other Copenhagen precepts. It conforms to Bohr's claim of "the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality": the nonlocal transfers violate the "the classical ideal of causality", and the conception of physical reality is radically altered.

To appreciate the nature of this alteration note that the key physical process involves the posing and answering of question with two allowed answers, $P = 1$ and $P = 0$. Thus the basic dynamical process is *informational* in character. The dynamics involves two kinds of choices that are indeterministic, at the present stage of theoretical development. Each quantum processor chooses questions, and nature chooses the answers. These answers are stored in the evolving physical reality S(t). This stored compendium of discrete answers has causal power: S(t) specifies the propensities for the posing and answering of future questions. Once the physical world is understood as a stored compendium of locally efficacious bits of knowledge, the instant transfers can be understood in terms of changes in "knowledge".

In the Copenhagen interpretation the pertinent knowledge was "our knowledge": it was conscious human knowledge of the kind we can describe and communicate to other human beings. This knowledge is the foundation of

human science. Von Neumann was concerned with this kind of knowledge, because he needed to show that his theory could generate the predictions of Copenhagen quantum theory. Although human beings, and human knowledge, play, therefore, a special role in the theory in its present state of historical development, our species should play no special role in a truly objective description of nature. Von Neumann's theory has, accordingly, been formulated here in terms of the more general concept of quantum information processors, of which human beings are the paradigmatic examples. However, other creatures and physical systems cannnot excluded, a priori, and the concept of "knowledge" will eventually need to be developed [9] to accommodate the precursors of human knowledge, namely the more primitive forms from which human knowledge emerged.

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